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Improving stormwater retention on green roofs

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ABSTRACT

Impervious surfaces such as roads, parking lots, and buildings along with the lack of investment in infrastructure has led to stormwater management problems such as flooding and combined sewage overflows, especially in urban areas. Therefore, there has been a concerted effort to design green roof systems to maximize stormwater retention and satisfy local stormwater codes. In this study, 21 green roof tables were constructed and utilized to compare nine green roof treatments including a roof water reservoir designed to provide temporary water storage (blue roof), two commercially available module systems, these module systems combined with a blue roof underneath (blue-green roof), rockwool, pavers, gravel, and the roofing membrane alone. All runoff events were analyzed together as one data set and then again when categorized by relative intensity as light (<7.0 mm [0.27 in]), medium (7.0 – 20.0 mm [0.27 in – 0.79 in]), or heavy (>20.0 mm [>0.79 in]). Adding the RoofBlue system to the LiveRoof Standard and Lite systems improved retention by 29.4% and 37.9%, respectively, during heavy rain events when stormwater runoff is most likely to be a problem. Overall, the rockwool and blue-green roof systems retained the greatest quantity of stormwater and were found to be comparable.

Key words: *blue roof, blue-green roof, mineral wool, rockwool, stormwater runoff*

INTRODUCTION

Green roofs partially replace the vegetation that was displaced when buildings are constructed. In doing so they can provide numerous environmental, economic, and social benefits that can help offset the negative aspects of impervious surfaces resulting from roads, parking lots, and buildings, especially in the urban environment. Green roofs can improve stormwater management; they reduce runoff and improve water quality, conserve energy typically used for heating and cooling, mitigate the urban heat island, increase longevity of roofing membranes, reduce noise and air pollution, sequester carbon, make use of unused space for local food production, increase urban biodiversity by providing habitat for wildlife, improve human health, and provide a more aesthetically pleasing environment to work and live (Czemiel Berndtsson 2010; Eakin et al., 2015; Eksi et al., 2017; Oberndorfer et al., 2007; Rowe 2011; Schultz et al., 2018; Whittinghill and Rowe 2012; Whittinghill et al., 2014).

Even though green roofs can provide the above listed benefits, the driving force for most green roof installations is stormwater management. This is because they can lessen the chances of combined sewer overflow (CSO) events, decrease flooding, and decrease the quantity of surface contaminants that may flow into our waterways. When cities do not have separate stormwater and sewer systems, both are funneled through the same pipe. If these pipes experience a rain event where the volume of runoff exceeds the capacity of the stormwater system, then a CSO occurs where raw untreated sewage flows out of relief points into our waterways. There are 772 such communities in the U.S. that do not have separate sewer and stormwater systems (US EPA, 2008). For example, about half of all rainfall events in New York City result in a CSO event and collectively they dump 40 billion gallons of untreated wastewater into New York's surface waters every year (Cheney 2005). By retaining stormwater, green roofs decrease the chance of a CSO event and reduce the costs associated with stormwater systems and treatment plants because they do not have to be as large to handle peak runoff or overflows (Rowe 2011).

Green roofs play a role in alleviating problems caused by excess stormwater by reducing the overall amount of runoff, attenuating peak runoff, and delaying runoff. Water retained on plant foliage or in the substrate will eventually evaporate or will be transpired by plants back into the atmosphere. In addition, water that does runoff is delayed over the course of time it takes for the substrate to become saturated before it drains. Because runoff is released over a longer period, green roofs can help keep municipal stormwater systems from overflowing, reduce the probability of CSO events when stormwater and sewage systems are not separated and the system cannot handle the volume, and reduce potential erosion of stream banks and water quality downstream (Rowe 2011). For example, if 20% of buildings in Washington, DC, had green roofs, they could store approximately 958 million liters (253 million gallons) of rainwater in an average year (Deutsch et al., 2005).

Several factors influence the ability of a green roof to serve as a stormwater management tool. Some, such as the intensity, duration, and frequency of storms cannot be controlled. However, we can design green roofs to improve their stormwater retention capacity with our selection of plant choices, substrate composition and depths, drainage layers, and irrigation practices. All factors can influence pre-existing substrate moisture (VanWoert et al., 2005).

There are green roof designs, systems or combinations of system components that can further improve retention. Some examples that have been implemented or are currently being tested including indented cups in the drainage layer, water wicking materials, the use of mineral wool or rockwool growth substrate composed of synthetic (silicate) fibers, blue roofs (water storage layer on a roof), and blue-green roofs (addition of a water storage layer underneath a green roof system) to maximize stormwater retention (Bollman et al., 2019; Droz et al., 2021; Eksi and Rowe 2016; Garner et al., 2015; Martin III and Kaye 2020, Majkovič et al. 2016; Matlock and Rowe 2016; Schultz et al., 2018; Shafique et al., 2016a; Shafique et al., 2016b; Whittinghill et al., 2015). The objective of this study was to compare newer green roof systems (blue and blue-green roofs) with some existing products that are already on the market as well as bare roofs without any green roof components.

MATERIALS AND METHODS

Treatments

Twenty-one roof tables with dimensions of 1.22 m x 1.22 m (4.0 ft x 4.0 ft) were constructed at Hortech Nursery (Nunica, MI). Each table was covered with a 60 mil EPDM (ethylene propylene diene monomer) rubber waterproofing membrane. Gutters constructed of PVC were attached on the low end of the tables to direct stormwater runoff through a funnel into plastic tubs. Gutters were covered with aluminum flashing to ensure that collected stormwater was limited to rain falling on the tables only. All tables were set at a 2% slope with the low end of the table facing south to maximize sun exposure (Figure 1).

1A. Overview

1B. Individual runoff table prior to treatment installation

Figure 1. Overview of the research site and individual table.

The experimental model was a completely randomized design (CRD) with one factor replicated three times. Green roof system was the single factor analyzed with six treatments replicated three times. Treatments 7 (Membrane only), 8 (Gravel ballast), and 9 (Gravel + LiveSponge™) were not replicated due to budget and space limitations. The treatments (Figure 2, Figure 3) were:

1) LiveRoofStandard = LiveRoof Standard module with 10.8 cm (4.25 in) of substrate depth. When module is vegetated and fully saturated it weighs 12.7 kg (28 lbs).
2) LiveRoof Standard + RoofBlue RETAIN = LiveRoof Standard module with 10.8 cm (4.25 in) of substrate depth over RoofBlue RETAIN system, an experimental water reservoir under the module (a type of blue-green roof).
3) LiveRoof Lite = LiveRoof Lite module with 6.4 cm (2.5 in) of substrate depth. When module is vegetated and fully saturated it weighs 7.3 kg (16 lbs).
4) LiveRoof Lite + RoofBlue RETAIN = LiveRoof Standard module with 6.4 cm (2.5 in) of substrate depth over the RoofBlue RETAIN system which is an experimental water reservoir under the module (a type of blue-green roof).
5) Substrate + Rockwool = 7.6 cm (3 in) of substrate over 5.1 cm (2 in) of Grodan PP 100/100 rockwool (Rockwool, B.V., Roermond, Netherlands) placed over a thin J-drain board (JDR Enterprises, Alpharetta, GA).
6) RoofStone Pavers = LiveRoof RoofStone 5.1 cm (2 in) thick concrete pavers over a 5.1 cm (2 in) tall plastic integrated base.
7) Membrane only = 60 mil EPDM waterproofing membrane.
8) Gravel Ballast = 5.1 cm (2 in) of smooth granite aggregate from nearby quarry (Meekhof Lakeside Dock, Nunica, MI).
9) Gravel + RoofSponge™ = 5.1 cm (2 in) of gravel over a mat composed of water adherent non-degradable polyester fibers (a type of blue roof).

2A. LiveRoof Standard

2B. LiveRoof Lite

2C. Substrate + Rockwool

2D. RoofStone Pavers

2E. EPDM Membrane only

2F. Gravel ballast

Figure 2 Cross sections of green roof systems used in the study. Cross sections of treatments Standard +RoofBlue RETAIN, Lite + RoofBlue RETAIN, and Gravel + RoofSponge™ are not shown as they are proprietary.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
SB	L	RS	R	M	R	LB	S	G	L	RS	L	RS	S	R	SB	S	LB	GR	SB	LB

Figure 3. Experimental layout of treatments: LiveRoofStandard (S); LiveRoof Standard + RoofBlue RETAIN (SB); LiveRoof Lite (L); LiveRoof Lite + RoofBlue RETAIN (LB); Substrate + Rockwool (R); RoofStone Pavers (RS); Membrane only (M); Gravel Ballast (G); and Gravel + RoofSponge™ (GR).

Regardless of treatment, all plant material was grown for 12 months in standard LiveRoof 30.5 cm wide x 61 cm long x 10.8 cm deep (12 in x 24 in x 4.25 in) modules. Species consisted of a mix of 11 stonecrops: *Sedum album* `Coral Carpet'; *S. ellacombianum*; *S. floriferum* `Weihenstephander Gold'; *S. hybridum* `Immergrunchen'; *S. hybridum* `Czar's Gold'; *S. middendorffianum* `Striatum'; *S. reflexum* `Angelina'; *S. spurium* `John Creech'; *S. spurium* `Pink Jewel'; *S. spurium* Roseum'; and *S. spurium* `Royal Pink'. When placed above rockwool, the planting was removed from the standard LiveRoof module, the substrate profile was trimmed to a depth of 7.6 cm (3 in), and then placed above the rockwool. Similarly, the standard LiveRoof profile was trimmed to a depth of 6.4 cm (2.5 in) before placement into the LiveRoof Lite module. For the LiveRoof Standard treatments, standard modules were simply placed on top of the collection table. Plants in all treatments were grown in the same aggregate growing substrate, had an identical assortment of mature plants, and had achieved full coverage (no substrate exposed) before data collection commenced on March 20, 2020. The initial physical properties of the growing substrate are shown in Table 1.

Table 1. Initial physical properties of substrate.

Property	Value	Method
Sand1 (%)	84	Bouyoucos 1962
Silt (%)	12	Bouyoucos 1962
Clay (%)	4	Bouyoucos 1962
Soil Textural Class	Loamy Sand	Bouyoucos 1962
Bulk Density (g/cm3)	1.04	Ferguson et al., 1960
Capillary Pore Space (%)	19.93	Ferguson et al., 1960
Non-Capillary Pore Space (%)	27.70	Ferguson et al., 1960
Infiltration Rate (cm/hr)	90.60	Ferguson et al., 1960
Water Holding Capacity @ 0.01 MPa (%)	19.17	Ferguson et al., 1960
Organic Matter by LOI @ 360 °C (%)	4.9	NCR-13, 1998

Analysis per A&L Great Lakes Laboratories, Inc., Ft. Wayne, Indiana

[1] The 84% sand fraction is based on physical particle size analysis through the screening process at the laboratory. The original mixture consisted of 5% sand and 65% haydite (Hydraulic Press Brick Company, Brooklyn, IN).

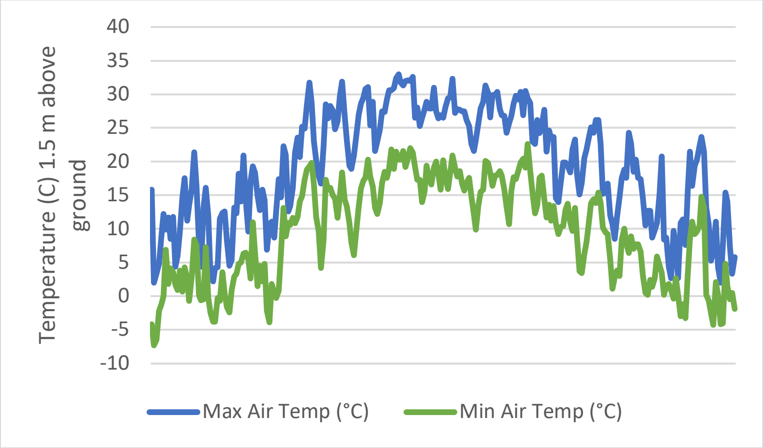
Rockwool is often used in the horticulture industry to grow plants. In has many favorable properties in green roof applications in that it possesses a high water holding capacity and is approximately ten times lighter than typical green roof aggregate substrates (Garner et al., 2015; Majkovič et al., 2016). Both properties are generally desirable for green roof applications as it serves as a water reservoir and a secondary substrate layer for rooting, can provide extra evaporative cooling due to the higher water content, and can lead to a reduction in weight load per given substrate depth (Wong and Jim 2014). Manufacturers also claim that it is stable, durable, and a renewable resource (Garner et al., 2015).

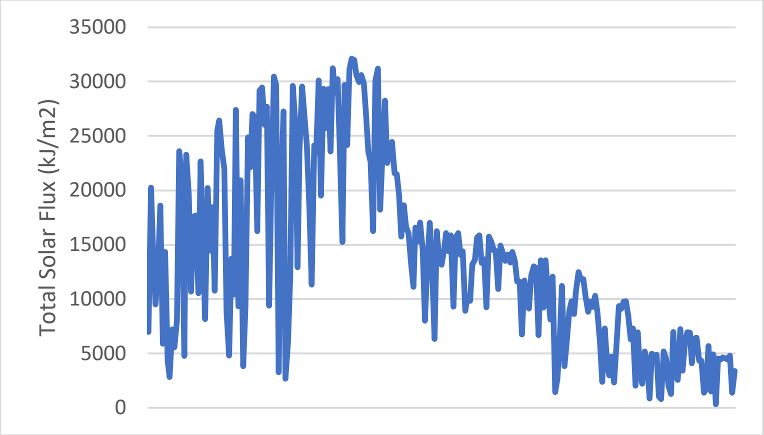
To avoid confusion, the terms rockwool and mineral wool are often used interchangeably, and this is correct to some extent. Both are manufactured from molten rock and then spun into thin, long silicate fiber strands, which are compressed to create products such as thermal insulation, sound proofing, and horticultural growing substrates. The main difference is the percentage of the raw material used in manufacturing. Rockwool is comprised primarily of basalt, whereas the main ingredient in mineral wool is mineral waste residue. Even though the terms are often used interchangeably, rockwool is a specific product made by Rockwool. However, mineral wool is made by other manufacturers. Grodan, B.V. is part of the

Rockwool Group of companies and therefore the mineral wool growing substrate is referred to as rockwool in this paper (Grodan, B.V., 2021; Grodan, B.V. 2022; Rockwool, B.V. 2022).

Data Collection

Weather data was collected continuously throughout the study period (March 20, 2020, to November 23, 2020) for temperature, solar flux, and precipitation from the Michigan Automated Weather Network's Conklin/Wright weather station (www.enviroweather.msu.edu) located approximately 16 km (10 miles) from the research site (Figure 4). Because the weather station was too far away to provide reliable precipitation values, rainfall for each individual event used for data analysis was measured with a Tru-Chek rain gauge (Edwards Manufacturing Co., Albert Lea, MN) located adjacent to the green roof test tables. Following each rain event, runoff that drained through the gutter into the collection tubs was measured by weight to calculate the percent retention. Weights were recorded within an hour after the cessation of runoff during normal business hours. There was nobody available to make measurements during the night and it was also assumed that there would be no appreciable evaporation during the evening and nighttime hours. Precipitation data from the Conklin/Wright weather station was included to provide general information on the time elapsed between rainfall events. Similarly, temperature and solar flux provided some insight into potential evapotranspiration rates and the relative speed that the substrates would dry out.





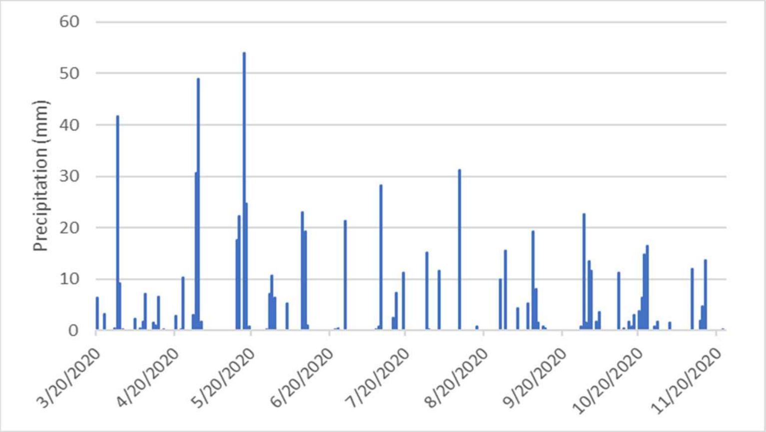


Figure 4 Daily maximum and minimum temperatures (°C) 1.5 m above ground, total daily solar flux (kJ/m2), and precipitation (mm) throughout the data collection period (March 20, 2020, to November 23, 2020). Data is from the Michigan Automated Weather Network's Conklin/Wright weather station located approximately ten miles from the research site (www.enviroweather.msu.edu).

Data Analysis

Retention data were analyzed as a percentage of total rainfall for each rain event. Retention is defined here as precipitation that did not exit the platforms so was stored in the system. Independent rain events were defined as precipitation events that were separated by six or more hours. In the event runoff was still occurring six hours after the first event, the two events were combined. All runoff events were analyzed together as one data set from measurements from each individual rain event and then again when categorized by relative intensity as light (<7.0 mm [0.27 in]), medium (7.0 – 20.0 mm [0.27 in – 0.79 in]), or heavy (>20.0 mm [>0.79 in]). The range of each category was chosen to obtain rain event sample sizes that were similar across all three categories with 15, 16, and 12 light, medium, and heavy rain events, respectively. There was a total of 43 rain events used in the analysis.

The experimental model was a completely randomized design (CRD). Mean percent retention per rain event was analyzed using an ANOVA model with green roof system and rainfall category as fixed effects (PROC MIXED, SAS version 9.4, SAS Institute, Cary, NC). The dependent variable was retention with independent variables of green roof system (the treatment) and rain category (all and then heavy, medium, and light). Significant differences between treatments were determined using multiple comparisons by the LSD (least significant difference) test.

RESULTS

During the 249 days of the study, 43 rain events were measured ranging from 0.5 mm (0.02 in) on June 2 to 119.4 mm (4.7 in) on April 30. Winter was excluded as frozen precipitation results in unreliable data. The 43 rain events measured during temperatures above 0°C (32°F) were analyzed together and then categorized into light (<7.0 mm) (0.27 in), medium (7.0 – 20.0 mm) (0.27 in – 0.79 in), or heavy (>20.0 mm) (>0.79 in) rain events. Rainfall events were divided by volume to point out how the different treatments performed during heavier rain events when municipal stormwater systems are most likely to be stressed (Getter et al., 2007; VanWoert et al., 2005). Daily maximum and minimum ambient air temperatures measured at a nearby weather station ranged from 2.2°C (36.0°F) to 32.6°C (90.7°F) and -4.3°C (24.3°F) to 22.6°C (72.7°F), respectively (Figure 4). Daily total solar flux ranged from a high of 32,099 kJ/m^{-2} on June 14 to a low of 305 kJ/m^{-2} on November 15. Although evapotranspiration (ET) was not measured, temperatures and solar flux provide some insight into how rapidly the substrate would dry out between rain events.

The lowest retention for an individual rain event occurred for all treatments on April 30 when the site received 119.4 mm (4.7 in) of rainfall. During this rain event retention dropped an average of 54.4% compared to the mean overall retention for the entire study. Retention percentages for specific treatments decreased down to 12.9% (LiveRoof Standard), 16.7% (LiveRoof Standard + RoofBlue RETAIN), 10.7% (LiveRoof Lite), 15.0% (LiveRoof Lite + RoofBlue RETAIN), 16.8% (Substrate + Rockwool), and 9.0% (RoofStone Pavers) for this rain event. Dropping this data point from the analysis as an outlier was considered. However, with the ever-growing impact of climate change, high rainfall events may be the norm in the future. In fact, rainfalls of this magnitude have occurred twice since the completion of this study.

When all rain events were combined, both the LiveRoof Standard and Lite systems equipped with the RoofBlue RETAIN as well as the Substrate + Rockwool treatments retained the greatest quantity of stormwater with 81.9%, 82.0%, and 81.1% retention, respectively (Table 2, Figure 5). These three systems performed equally ($p \leq 0.01$). Adding the RoofBlue system to the LiveRoof Standard (10.8 cm [4.25 in] substrate depth) and Lite (6.4 cm [2.5 in] depth) systems improved retention by 11.2% and 13.8%, respectively. This suggests that the RoofBlue system had a greater effect on stormwater retention than the substrate itself. All of these systems show the major impact that green roofs have on stormwater retention compared to the Membrane only treatment that only retained 3.0% of the rain that fell on it. Even the RoofStone pavers (30.7%) and Gravel Ballast (30.5%) treatments improved retention significantly ($p \leq 0.01$), although these numbers can be skewed by light rain events where little water exits the roof. Adding the RoofSponge™ under the gravel ballast increased retention by 26% compared to the gravel by itself, showing a significant improvement even without plants or growing substrate. Although it was not tested in this study, combining the RoofSponge™ with green roof components might improve retention further.

Table 2. Mean percentage ± the standard deviation of total rainfall retention over the study period (March 20, 2020 to November 23, 2020) from the six green roof system treatments.

Treatment[a]	Light[b] (%)	Medium (%)	Heavy (%)	Overall (%)
LiveRoof Standard	98.7 ± 4.9 bB[c]	63.7 ± 30.4 aB	45.0 ± 35.5 aB	70.7 ± 34.2 B
LiveRoof Standard + RoofBlue RETAIN	97.5 ± 12.3 bB	72.9 ± 33.1 aB	74.4 ± 38.9 aC	81.9 ± 31.6 C
LiveRoof Lite	99.0 ± 3.8 cB	63.3 ± 31.6 bB	36.2 ± 30.4 aAB	68.2 ± 35.5 B
LiveRoof Lite + RoofBlue RETAIN	98.6 ± 4.4 bB	72.3 ± 32.4 aB	74.1 ± 40.3 aC	82.0 ± 31.4 C
Substrate + Rockwool	99.7 ± 1.9 bB	71.5 ± 32.8 aB	70.8 ± 36.7 aC	81.1 ± 30.9 C
RoofStone Pavers	46.5 ± 26.9 bA	23.6 ± 12.4 aA	20.5 ± 13.3 aA	30.7 ± 22.1 A

[a] Replicated treatments

1) LiveRoof Standard = LiveRoof Standard module with 10.8 cm (4.25 in) of substrate depth.
2) LiveRoof Standard + RoofBlue RETAIN = LiveRoof Standard module with 10.8 cm (4.25 in) of substrate depth over RoofBlue RETAIN system.
3) LiveRoof Lite = LiveRoof Lite module with 6.4 cm (2.5 in) of substrate depth.
4) LiveRoof Lite + RoofBlue RETAIN = LiveRoof Standard module with 6.4 cm (2.5 in) of substrate depth over the RoofBlue RETAIN system.
5) Substrate + Rockwool = 7.6 cm (3 in) of substrate over 5.1 cm (2 in) of Grodan PP 100/100 rockwool.
6) RoofStone Pavers = LiveRoof RoofStone 5.1 cm (2 in) thick concrete pavers over a 5.1 cm (2 in) tall plastic integrated base.

[b] Rain event categories were light (<7.0 mm [<0.27 in]) (n = 15 x 3), medium (7.0–20.0 mm [0.27-0.79 in]) (n = 16 x 3), and heavy (>20.0 mm [>0.79 in]) (n = 12 x 3), and overall (n = 43 x 3).

[c] Mean separation in rows and columns by LSD (P<=0.05). Lowercase letters denote comparisons across rain categories within individual treatments. Uppercase letters in columns denote differences among treatments.

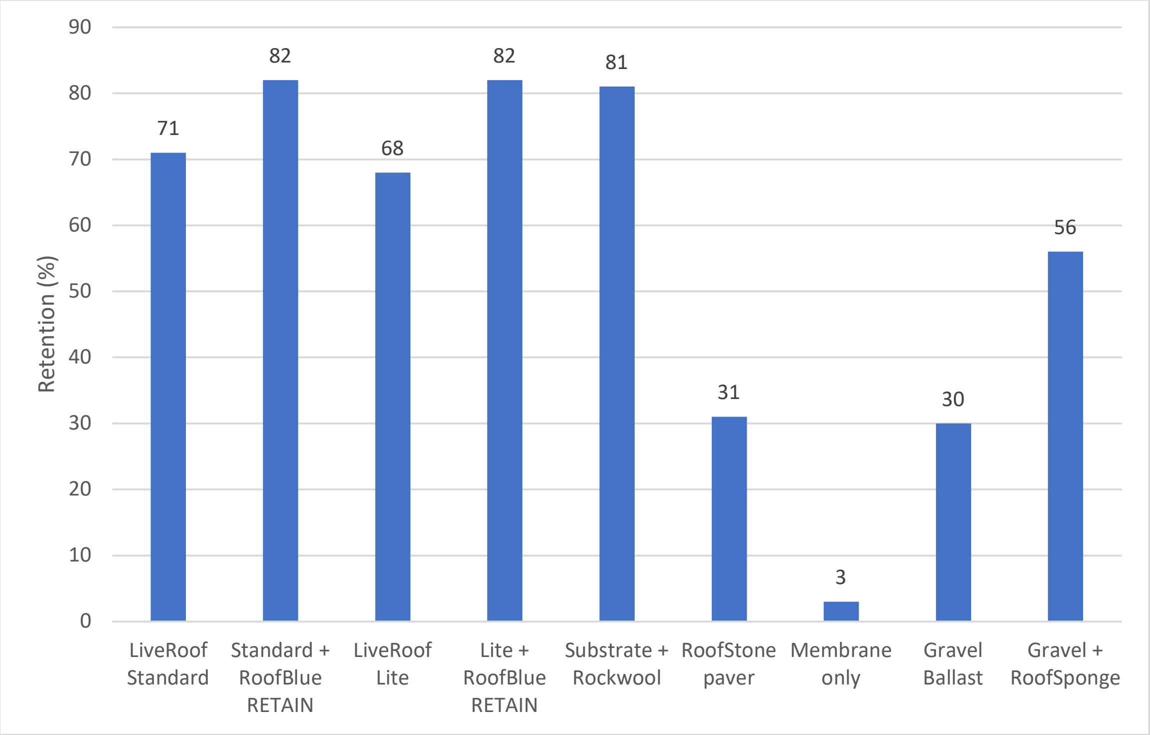


Figure 5. Stormwater retention for all rain events over the study period (March 20, 2020, to November 23, 2020). The first six treatments (from left to right) were replicated three times. Membrane only, Gravel ballast, and Gravel + RoofSponge™ had one replication.

When rain events were categorized into light, medium, and heavy rainfalls, as rainfall amounts increased, retention decreased (Table 2, Figure 6). There is a limit on the free space that can hold water in every green roof system. All treatments experienced a significant decrease in retention from light to medium rainfall events. However, the LiveRoof Lite treatment also significantly dropped an additional 27.1% in retention from the medium (63.3%) to the heavy (36.2%) rainfall category ($p \leq 0.01$). Similarly, the LiveRoof Standard system dropped 18.7% (from 63.7% to 45.0%) although this value was not statistically different. In contrast, retention did not change from medium to heavy rainfall events when the RoofBlue RETAIN system was added to the LiveRoof systems or for the Substrate + Rockwool system or the RoofStone pavers (Table 2, Figure 6). Quantitatively, the RoofSponge™ also behaved in this manner.

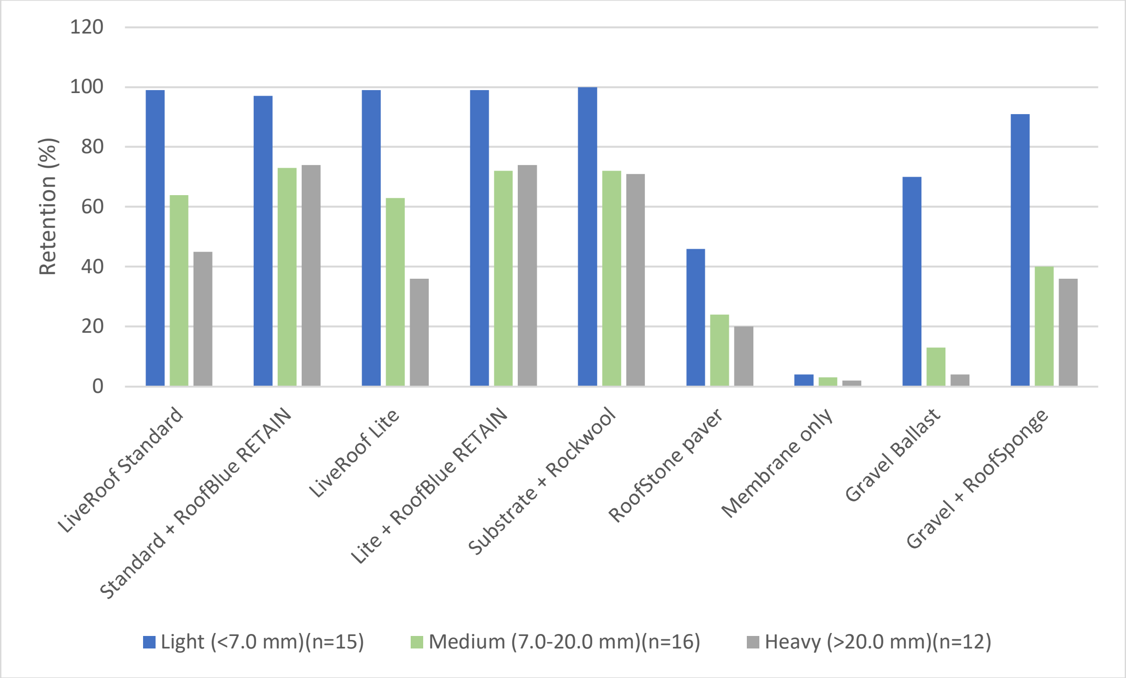


Figure 6. Stormwater retention for light, medium, and heavy rain events over the study period (March 20, 2020, to November 23, 2020). The first six treatments (from left to right) were replicated three times. Membrane only, Gravel ballast, and Gravel + RoofSponge™ had one replication.

When comparing treatments within rainfall categories, there were no differences among the LiveRoof Standard, LiveRoof Standard + RoofBlue RETAIN, LiveRoof Lite, LiveRoof Lite + RoofBlue RETAIN, and the Substrate + Rockwool, treatments for either the light or medium rainfalls of < 20 mm (0.79 in). However, during heavy rain events, the LiveRoof Standard and Lite paired with RoofBlue RETAIN and Substrate + Rockwool outperformed LiveRoof Standard and LiveRoof Lite without the RoofBlue RETAIN addition (Table 2, Figure 6). The LiveRoof Standard + RoofBlue RETAIN (74.4%) and LiveRoof Lite + RoofBlue RETAIN (74.1%) quantitatively held more water than the Substrate + Rockwool treatment (70.8%), but statistically there were no differences. The LiveRoof Lite also experienced a greater quantitative decrease in retention compared to the LiveRoof Standard system during heavy rain events. The LiveRoof Lite has a shallower substrate depth than the LiveRoof Standard. Adding the RoofBlue system to the LiveRoof Standard and Lite systems improved retention by 29.4% and 37.9%, respectively, during heavy rain events.

DISCUSSION

Within a given treatment, the variation in retention for similar rain events can be attributed to rainfall volume, intensity, duration, and pre-existing substrate moisture content. Even though rain events in this study were measured as total volume per individual rain event and not over time, the effect of pre-existing moisture content can be observed in the data. For example, the LiveRoof Lite module retained 65.4% of a 19.05 mm (0.75 in) rainfall on October 13 when it had been 8 days since the last rain of 33.0 mm (1.3 in) on October 5. The same treatment only retained 4.3% of a 19.05 mm (0.75 in) rainfall on October 22 when it had rained 7.6 mm (0.3 in) the day before. A green roof will normally reduce peak runoff as water must drain through the growing substrate even when it is already wet. However, when the preceding weather conditions are drier and thus the substrate is drier, runoff is expected to be delayed over a longer time period, thus reducing the peak runoff quantity even further. The peak flow reduction and the capacity for extending the runoff over longer periods is especially important when municipal stormwater and sewage systems are not separated and peak runoff volume cannot be handled by the existing infrastructure, thus resulting in a CSO event (Czemiel Berndtsson 2010; VanWoert et al., 2005). Peak runoff reduction can also help alleviate capacity issues for combined sewer systems such as basement sewer backups and street flooding from manholes as well as other issues with separated systems such as erosion and localized flooding.

During heavy rain events, the treatment containing rockwool increased water retention over the standard green roof modules, but not those with the RoofBlue RETAIN addition ($p \leq 0.01$). Although rockwool has many positive characteristics, it requires a lot of energy to manufacture so its embodied energy is quite high. The life cycle analysis of a green roof substrate considers all the energy required to produce the product from mining-excavation, pickup, processing, transportation, and total decomposition (Kotsiris et al., 2019). The manufacturing process of rockwool produces six times more CO_2 emissions than if pumice is used as the aggregate in a green roof substrate (Kotsiris et al., 2019). However, aggregates such as heat-expanded slate and shale also require a lot of energy to produce. For example, 89% of the embodied energy tied up in constructing the green roof on the Plant and Soil Sciences Building at Michigan State University was tied up in the heat-expanded slate portion of the substrate (Getter et al., 2009). In contrast, in the Kotsiris et al. (2019) study, the simulated model estimated reduction in annual CO_2 emissions due to energy savings and CO_2 capture by plants was many times greater than the CO_2 emissions that was emitted from roof construction. The roof consisted of a concrete deck and was planted with brushwood lavender (*Lavandula angustifolia*) in a coarse aggregate mix of 65% pumice, 30% organic compost, and 5% Zeolite (v/v) that were sourced locally.

Other negative and sometimes debated claims regarding rockwool include a loss of performance due to compression of the material when covered with substrate. It is also hydrophobic and can dry out the traditional overlaying growth substrate faster and is not recyclable (at least for products that contain phenol resin or phenol-urea-formaldehyde resin as a binder). The Grodan product used in this study was composed of synthetic vitreous (silicate) fibers bonded with a thermosetting phenolic resin which had been urea extended (Grodan 2021). There are also potential health issues as the fiber dust has been classified by the European Union as an irritant (transient mechanical) to the skin, upper respiratory system (mucous membranes), and to the eyes (Grodan 2021).

The blue roof and blue-green roof treatments also improved water retention. To avoid possible confusion regarding the terms blue roof and blue-green roof, a blue roof is defined as a non-vegetated system that is designed to provide temporary water storage that is gradually released, whereas blue-green roofs are vegetated green roofs with additional water storage capacity beneath the growing substrate to facilitate in stormwater retention (Shafique et al., 2016a; Shafique et al., 2016b). Thus, water may be retained on a blue roof by some other mechanical means than vegetation growing in a green roof substrate. One could say that all blue-green roofs are blue roofs, but not all blue roofs are blue-green roofs. The Standard + RoofBlue RETAIN and Lite + RoofBlue RETAIN are blue-green roofs, whereas the Gravel + RoofSponge™ treatment would be considered a blue roof as no plants or substrate were included. The RoofSponge™ treatment may perform comparably to a blue-green or rockwool roof if substrate and plants overlay the system instead of just a gravel ballast, but this was not tested.

In this study, both RoofBlue RETAIN systems that were added to the standard and lite modules were superior in retaining runoff compared to the standard and lite modules by themselves. This agrees with the work done by Droz et al. (2021) who compared a conventional green roof with 15 cm of substrate to a blue-green roof with 15 cm of substrate plus a 15 cm deep reservoir. Not only did the blue-green roof hold more water, but it also experienced zero runoff over the year long duration of the study. It was also significantly heavier which could limit the number of roofs where it would be feasible (Droz et al., 2021). The water holding capacity of any green roof system can be significantly improved by adding a storage layer (blue-green roof) underneath a green roof system (Martin III and Kaye 2020). In addition, in our study the use of a blue-green roof (RoofBlue RETAIN) as a water storage reservoir under the green roof modules (with 10.8 cm [4.25 in] or 6.4 cm [2.5 in] of substrate) were found to be comparable to the use of 7.6 cm (3 in) of substrate over 5.1 cm (2 in) of rockwool.

Blue-green roof and rockwool performance is predicted to vary with depth of the water reservoir and thickness of the rockwool. Doubling the depth of a blue-green roof reservoir will double the volume of water that could be retained, however, doubling the depth of a rockwool layer will not double the retention capacity as water will still drain. It is also possible that the added water retained by these systems may reduce the number of roofs where they could be installed because of the added weight.

CONCLUSIONS

Green roofs are effective at reducing runoff from buildings and new innovations in technology can further improve retention. Adding the RoofBlue system to the LiveRoof Standard and Lite systems improved retention by 29.4% and 37.9%, respectively, during heavy rain events when stormwater runoff is most likely to be a problem. The use of a blue-green roof (RoofBlue RETAIN) as a water storage reservoir under the green roof modules were found to be comparable to the substrate/rockwool treatment and these treatments retained the greatest amount of stormwater runoff. Stormwater management can be a problem, especially in urban locations. To help alleviate this problem and to encourage improved green roof systems, some North American cities such as Portland, San Francisco, and Toronto have adopted mandates that require green roofs in certain situations that will help these cities become more sustainable (Savarani 2019: US EPA 2022). New innovations in design and materials such as those tested in this study show promise for achieving stormwater management goals and can aid in providing a sustainable built environment.

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